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Concept of Large Space Structure Systems Using Deployable Membrane Modules Embedded with Inflatable Tubes

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ABSTRACT

Adaptability of deployable membrane modules to hierarchical modular space structure systems is investigated, and possible construction scenarios to realize future large space structure systems such as solar power satellites are shown. Membrane modules spirally folded and actuated by inflatable tubes are considered as basic modules, and their effective combination of deployment and automatic assembly for space construction is presented.

Keywords: Deployable space structures, Hierarchical modular systems, Membrane elements, Spiral folding, Space construction

1. INTRODUCTION

In many present and future space structure systems, various elements and structures with deployable and/or adaptive functions are necessary due to the restriction of their volume during launch and due to the requirement of their adjustment in space environment. Present large space structure sysyems such as the international space station consist of various modules classified by their individual functions, and generally they are assembled by robotic arms through the operateion of astronauts. This construction scheme is considered to be a concentrated one, which needs vast amounts of construction resorces. But there might be another possibility to construct large space structure systems using uniforme modules with distributed simple construction functions. Structure systems to fit such a distruibuted construction scheme are hierarchical modular structure systems [1,2], and some of their construction schemes using regular fixed modules has been studied [3]. In this paper, adaptability of deployable membrane modules to hierarchical modular space structure systems is investigated, and possible construction scenarios of future large space structure systems such as solar power satellites, solar sail spacecraft and so on, are proposed.

Concepts of deployable membrane structures embedded with inflatable tube networks [4] seem to give simple deployment procedure. Using some of these membrane structures as a typical basic module of a hierarchical modular space structure system, its construction schemes could have more concrete possibility. They include both assembling sequences of membrane modules and their deployment procedures to get its final configuration. In the following sections, a hexagonal deployable membrane element with spiral folding pattern, a deployable structure composed of six

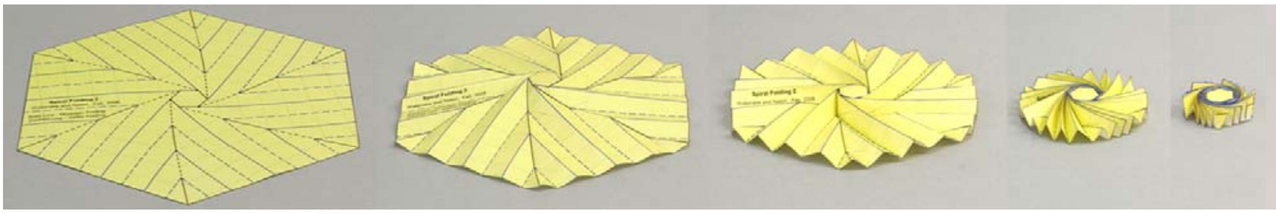


Figure 1. Paper craft (origami) model of spiral folding

membrane modules, possible construction scenarios of hierarchical modular structure systems, and conceptual extension of deployable membrane modules to three-dimensional structures are introduced.

2. DEPLOYABLE MEMBRANE MODULAR STRUCTURES

2-1. Basic deployable membrane module including inflatable tubes

A flat membrane surface can be folded around its center body such as shown in Fig. 1. It is folded in a zigzag manner along circumferential direction, and rolled up along radial direction. Folding lines are slightly curved due to thickness effect of membrane, which are composed of piecewise straight line elements along the outer shape of the center body, and when thickness is assumed to be zero they become straight; this folding pattern is called "spiral folding" [5]. It was studied at first for direct application to spinning solar sail spacecraft, and it was supposed to be deployed through the centrifugal force caused by spinning. For further various applications, it might be better to have other options for reliable deployment through other actuation forces. Membrane structures embedded with branching inflatable tubes are effectively used in the eclosion process of insects [6], and some trials to apply their basic concept to membrane structures have been already carried out [7, 8]. But complete embedding with inflatable tubes might be the result of optimization for their long history, and for actual engineering applications it seems to restrain structure systems too much. One example of candidates for appropriate deployable basic modules of future hierarchical modular space structure systems is a membrane module consisted of a membrane, inflatable tubes, and connecting cables (cable networks), and connecting cables or cable networks discretely connect membrane and inflatable tubes. Its scaled model for laboratory experiments is shown in Fig. 2, and in this case connecting cable straps to fit the outer circumferential inflatable tube are used. In this study, it is assumed that the membrane has thick property, and is spirally folded, and the inflatable tubes are relatively extensional for easy deployment. The membrane and the cables are rather inextensional to keep structural accuracy. Cables and/or cable networks are expected to cooperate well with membranes to provide efficient structure systems [9-11], and their node points are also used as interface points for other modules.

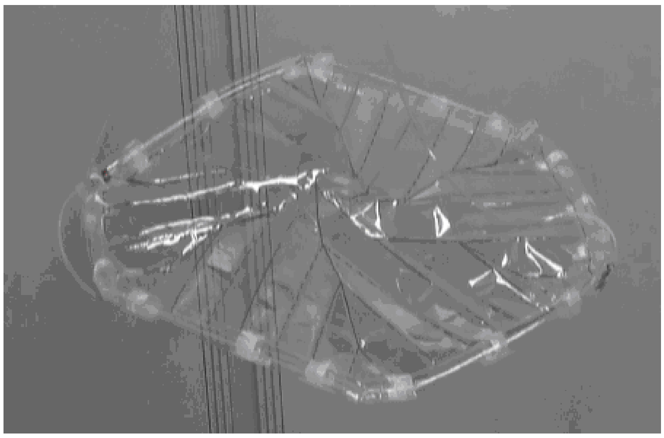


Figure 2. Deployable membrane module

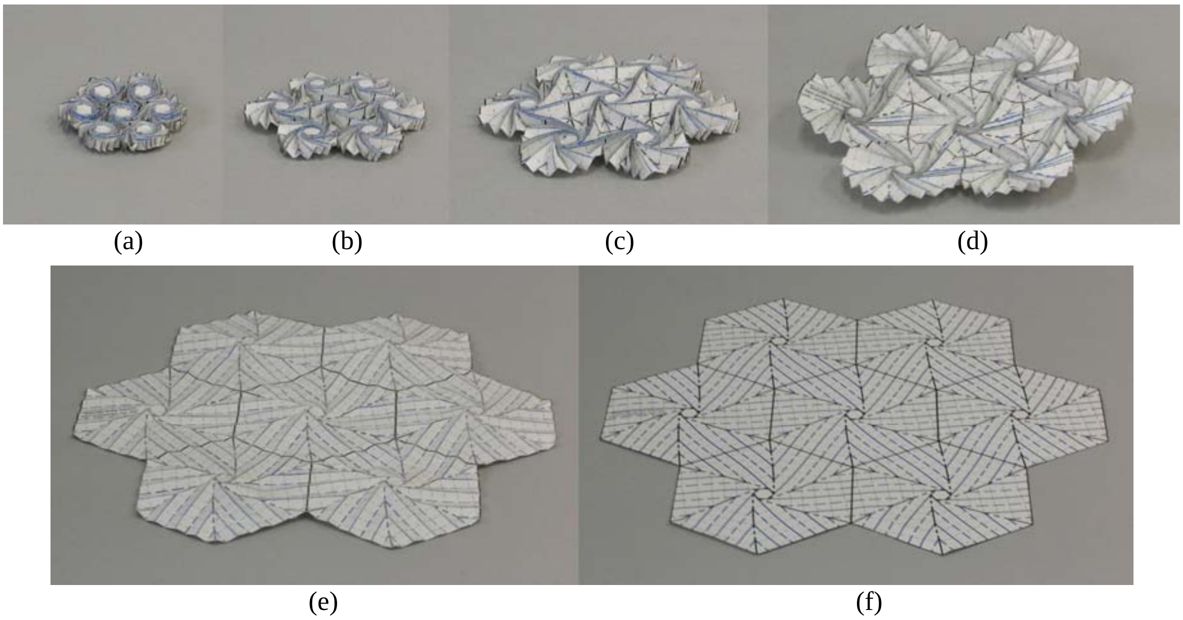


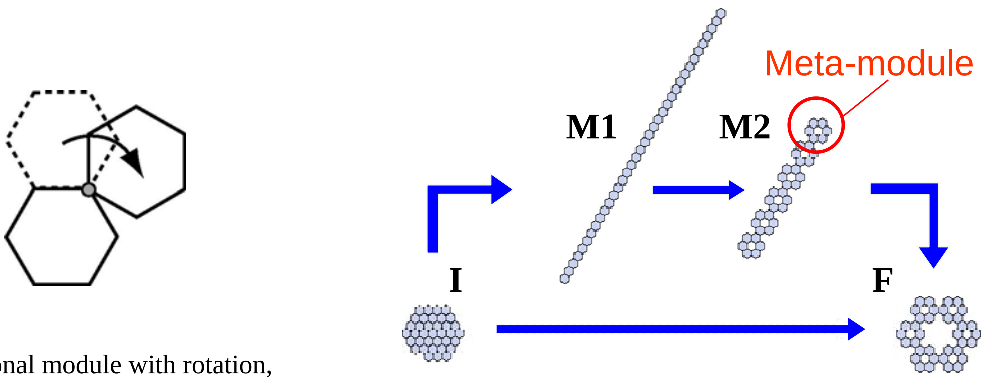
Figure 3. Conceptual paper craft model of modular deployable membranes with spiral folding

2-2. Deployable membrane modular structure with spiral folding

It is well known that regular hexagons tessellate flat surface completely, and replacing these hexagons to the deployable membrane modules stated in the previous section, we can easily get a deployable membrane modular structure. Figure 3 shows the deployment sequence of its conceptual paper craft model from packed configuration to deployed one. It is well shown that a thin flat surface is packed into a thick disk-like block shown in Fig. 3(a). If the process of deployment is completely synchronous in every module, all modules keep deployment in the same flat plane. Since there are some stiffened effects along folding lines especially in this kind of small paper craft models, some out of plane deformation (warped from flat configuration) is observed (Fig. 3(d)). The center module seems to be strongly restrained by surrounding six modules, and it is expected that a deployable membrane modular structure without center module would deploy more smoothly.

3. POSSIBLE CONSTRUCTION SCENARIOS OF LARGE STRUCTURE SYSTEMS

Some of future large space structure systems such as solar power satellites consist of many similar uniform modules, which appear repeatedly in the whole system, and each module could



(a) Hexagonal module with rotation, latch and release mechanisms

(b) Construction sinario of a hierarchical modular system

Figure 4. Automatic construction of a hierarchical modular system using regular fixed modules

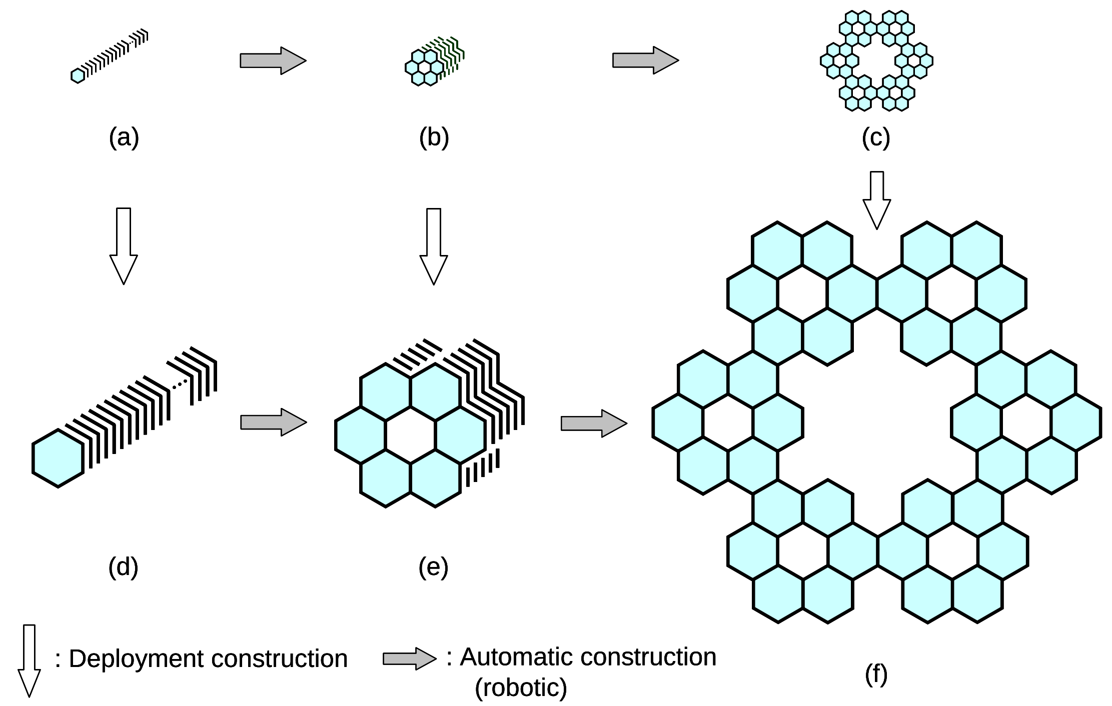


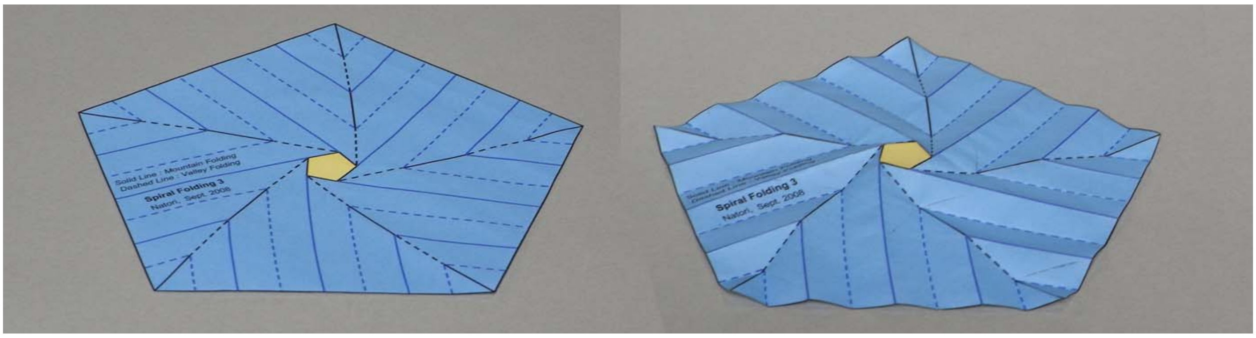
Figure 5. Possible construction scenarios of future large space structure systems

include the same simple function for construction. Automatic construction schemes using rigid modules having such simple mechanisms for self-assembly at their appropriate interface points show good alterable possibility [3]. Figure 4 illustrates one example of such construction schemes. Each hexagonal module has rotation, latch and release mechanisms at each apex, and changes its relative position around another module such as shown in Fig. 4(a). From the initial piled up configuration shown as I in Fig. 4(b), through the intermediate configurations M1 and M2, they can easily form the final configuration of F automatically. M2 is the straight line configuration composed of the second generation hierarchical modular structures (meta-modules), and F corresponds to the third generation structure. The configuration of the second generation structure corresponds to the one without the center module shown in Fig. 3(f). It has been shown that the direct automatic construction from I to F generally shows a low success rate due to the closed form characteristics of the final hierarchical modular configuration.

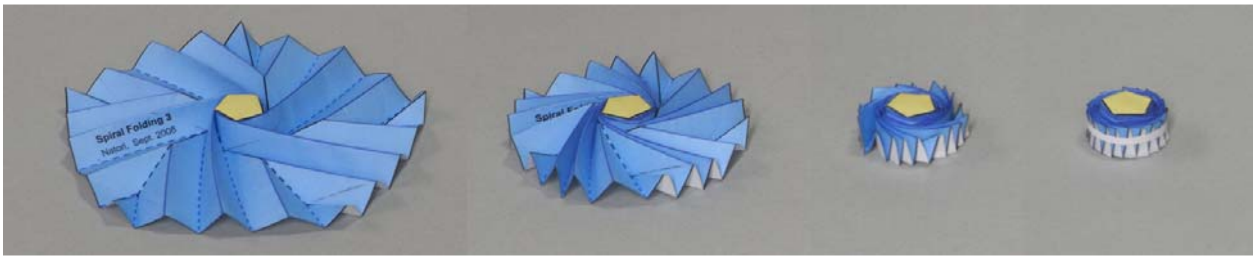
Including deployable membrane modules in the automatic construction schemes mentioned above, we can get more flexible construction scenarios for future large space structure systems such as illustrated in Fig. 5. If all modules are rigid ones, starting from initially piled up situation shown in Fig. 5(a) and following the same procedure as shown in Fig. 4(b), we can obtain the configuration of the third generation hierarchical modular structure shown in Fig. 5(c) through only automatic construction. If all modules are deployable ones, the configuration (c) changes through deployment construction to the larger one shown in Fig. 5(f), and in this case the route from the initial situation to the final configuration is as (a)-(b)-(c)-(f). There could be other two different routes to get the same final configuration; (a)-(d)-(e)-(f) and (a)-(b)-(e)-(f). In the case of sufficient transportation capability, the initial situation could be assumed to be the one shown in Fig. 5(b), and the routes (b)-(e)-(f) and (b)-(c)-(f) are acceptable. Some appropriate route would be chosen depending on mission requirements and technology maturity related to necessary deployable and self-assembly elements.

4. EXTENSION TO DEPLOYABLE THREE-DIMENSIONAL STRUCTURES

In the previous sections, the regular hexagonal deployable membrane module is treated as a



(a) (b)



(c) (d) (e) (f)

Figure 6. Pentagonal deployable module with spiral folding

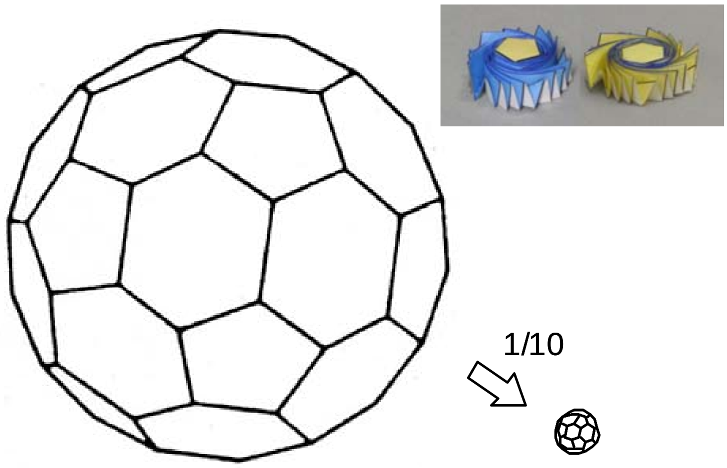


Figure 7. Example image of three-dimensional deployable membrane modular structures Truncated icosahedron (Fullerene)

basic module, but other polygonal modules are also available. For example the square deployable membrane modules can cover large square surface structures, and some combination use of different polygonal modules leads naturally to deployable three-dimensional polyhedral structures. Figure 6 shows a conceptual paper craft model of pentagonal deployable membrane module with spiral folding. Its combination use with hexagonal module makes a deployable truncated icosahedral (Fullerene) structure, a part of which would be a good approximation of reflector surface structures, and its image is shown in Fig. 7. In this case, in a packed configuration thick disk-like modules shown upper right in the figure must be connected each other in slightly inclined manner, and some folding patterns similar to bellows are applied to the connecting parts.

Once getting some appropriate deployable polyhedral module, it can be directly applied to three-dimensional hierarchical modular structure systems [2], and there could appear various deployable membrane modular structures.

5. CONCLUSIONS

Conceptual study to construct future large space structure systems using deployable membrane modules is introduced. Membrane modules spirally folded and actuated by inflatable tubes are considered as basic modules for hierarchical modular structure systems, and their effective combination of deployment and automatic assembly to construct large space structure systems such as solar power satellites is presented. Some extended concept of deployable membrane modules to three-dimensional structures is also introduced.

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REFERENCES

1. N. Kishimoto and M.C. Natori, "Hierarchical Modular Structures and Their Advantages for Future Large Space Systems," 14th Int'l. Conf. Adaptive Structures and Technologies (ICAST), Seoul, Korea, Oct. 2003, DEStech Publ. (June 2004), 350-359.
2. N. Kishimoto and M.C. Natori, "Hierarchical Modular Structures and Their Geometrical Configurations for Future Large Space Systems," J. Int'l. Assoc. Shell and Spatial Structures (IASS), Vol.47, No.3, Dec. 2006, pp.303-309.
3. K. Ukegawa and M.C. Natori, "Self-Assembly of Hierarchical Modular Structure Systems," 16th Int'l. Conf. Adaptive Structures and Technologies (ICAST), Oct. 2005, Paris, France.
4. N. Kishimoto, M.C. Natori , K. Higuchi, and K. Ukegawa: "New Deployable Membrane Structure Models Inspired by Morphological Changes in Nature," AIAA-2006-1898, 47th AIAA/ASME/ ASCE/AHS/ASC Structures, Structural Dynamics, and Materials (SDM) Conf., Newport, Rhode Island, USA (2006.5).
5. M.C. Natori1, H. Watanabe, N. Kishimoto, and K. Higuchi, "Folding Patterns of Deployable Membrane Space Structures Considering Their Thickness Effects," 18th Int'l. Conf. Adaptive Structures and Technologies (ICAST), Oct. 2007, Ottawa, Canada.
6. M.C. Natori, N. Kishimoto, K. Ukegawa and K. Higuchi, "Concepts of Morphological Changes in Bio-Systems and Artifacts," 3rd Int’l. Symp. Intelligent Artifacts and Bio-Systems, Sept. 2006, Daejeon, Korea.
7. K. Senda, N. Kishimoto, K. Higuchi, Y. Shoukaku, S. Mizuguchi, T. Ogasawara and T. Oda, "Finite Element Method Analysis and Experiment of 2-Dimensional Deployable Membrane Structures Embedding Inflatable Tubes," AIAA 2008-2054, 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials (SDM) Conf., April 2008, Schaumburg, Illinois.
8. H. Furuya, Y. Yoshida, A. Senba and I. Katagiri, "Properties of Plainly Composed Inflatable Panels," AIAA 2008-2050, 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conf, April 2008, Schaumburg, Illinois.
9. M.C. Natori, K. Higuchi, K. Sekine and K. Okazaki, "Adaptivity Demonstration of Inflatable Rigidized Integrated Structures (IRIS)," Acta Astronautica, 37, Oct. 1995, 59-67.
10. G. Greschik and M.M. Mikulas, "Design Study of a Square Solar Sail Architecture," AIAA 2001-1259, 42nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials (SDM) Conf., April 2001, Seattle, WA.
11. N. Yajima, N. Izutsu, H. Honda, H. Kurokawa and K. Matsushima, "Three-Dimensional Gore Design Concept for High-Pressure Balloons," J. Aircraft, Vol.38, No.4, July-August 2001, pp.738-744.